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Effect of Pad Surface Roughness on Material Removal Rate in Chemical Mechanical Polishing Using Ultrafine Colloidal Ceria Slurry

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In this paper, effect of ultrafine ceria (UFC) particle of which size is as small as 20 nm on CMP performance was investigated. Compared to conventionally used 100 nm abrasive particle which is made by calcination process, almost 80% scratch reduction was obtained by using UFC. However, a UFC slurry showed unstable material removal rate behavior from less than 200 Å/min to over 2000 Å/min, depending on polishing pad surface characteristics. As pad surface roughness increases, oxide removal rate using UFC drops abruptly to less than 200 Å/min. In order to use UFC for scratch reduction, the pad surface roughness optimization is necessary to avoid a sudden drop in the removal rate. This study gives a possible boundary for pad surface roughness for UFC application for CMP.

Keywords: CMP, ultrafine ceria, removal rate, polishing pad, surface roughness

1. INTRODUCTION

Chemical mechanical planarization/polishing (CMP) is widely used in the microfabrication industry due to its ability for both local and global planarization.[1-4] As devices have shrunk and the number of stack layers increased, the CMP process has become more popular. In addition, the emergence of 3D devices, through-silicon vias (TSV) packaging, and wafer-scale bonding technology requires more stringent CMP processing.[5,6] However, micro- and nano-scratches caused by the CMP process are severely detrimental to yield and reliability. Therefore, significant efforts have been focused on reducing scratches.[7-11] The major mechanism for scratch formation is direct contact between abrasive particles on the pad and the wafer surface.[7,8,12,13] Therefore, slurries comprising small, round abrasive particles are favorable for scratch reduction due to the smaller stress applied to the wafer. For dielectric CMP, the use of ceria-abrasive-based slurries is increasing because they provide superior CMP performances, including high selectivity, high removal rate, and high planarization efficiency.[14-18] Two common methods of synthesizing ceria particles are solid-state crushing and wet precipitation.[19] Most ceria-based slurries are manufactured via the solid-state process; this involves using a reagent to transform the raw ceria material (i.e., the cerium precursor) to cerium oxide, which is then mechanically crushed. The resulting ceria abrasive has an irregular shape and its size is controllable above ~100 nm. Contrary to the calcination method, colloidal ceria fabrication is a bottom-up process that involves the precipitation of ceria from an aqueous cerium salt solution followed by the growth of nuclei. Using this process, small and spherical ceria particles can be obtained by controlling the growth kinetics: a recent development in colloidal ceria manufacturing provided ultrafine ceria (UFC) particles that were close to 20 nm in diameter as an abrasive (secondary particle size).[9]

In CMP process, the material removal rate is associated with the polishing pad surface characteristics.[21-23] During the process, the pad surface is in direct contact with the wafer surface under pressure and velocity, which removes wafer material. Therefore, the roughness of the pad surface significantly impacts the material removal rate. For a ceria slurry, the contact area strongly affects the material removal rate; therefore, a smooth pad surface increases the rate of silicon oxide material removal due to the high contact ratio. Pad surface roughness is very sensitive to the conditioning process: Harsh conditioning conditions, such as higher conditioning force or the use of a low-grade diamond conditioner, commonly result in rough surfaces and a low material removal rate. A wide range of research on the effect of pad surface morphology and the use of various slurries has been reported.[20-23] However, studies on UFC slurry abrasives are uncommon. Although UFC provides significant scratch reduction, adverse effects such as poor selectivity, planarity, or material removal rate have not yet been investigated. In this study, the material removal rate trends using UFC were extensively investigated. Also, the relationship between the

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material removal rate and the pad surface roughness was examined. The results suggest that a certain pad surface roughness is critical in order to maintain a high material removal rate.

2. EXPERIMENTAL PROCEDURE

Two polishers were used for the CMP experiments. For scratch comparison, CMP was performed using an AMAT-LK (Applied Materials Inc., USA) with stop-on-polysilicon shallow-trench isolation (STI) wafers. After CMP, the wafer was inspected using a KLA Tencor inspection tool to determine the number of scratches. The effect of the pad surface roughness on the material removal rate was investigated using a GNP Poli-762 polisher (G&P Technology Inc., Korea) with a 300 mm, thermally grown tetraethyl orthosilicate (TEOS) oxide wafer. The Poli-762 polisher is a rotary polisher with a single platen that is used for research and development purposes. The details of the experimental conditions are summarized in Table 1. The material removal rate was determined by measuring the thickness of the TEOS blanket wafer before and after CMP using an ST-5000 tool (K-MAC Corporation, Korea), which uses a 12 V, 100 W halogen lamp as the reflectometer. Two kinds of ceria-based slurries were prepared. Calcined ceria and UFC slurries, which are referred to as Slurry A and Slurry B, respectively, were obtained from a CMP slurry supplier in order to compare the effect of using each slurry on scratch generation. Calcined ceria, which contains ~100 nm particles, and ultrafine colloidal ceria, which contains ~20 nm particles, were prepared and then characterized via transmission electron microscopy (TEM). The characteristics of the ceria slurries used in this experiment are given in Table 2. An IC1010 pore pad from Dow Corporation was used as the polishing pad. In order to control the polishing pad surface roughness, different types of conditioners were used and the conditioner down force was varied. The diamond grade indicates the sharpness of the diamond grit: A low-grade conditioner contains diamonds with sharp edges, whereas a high-grade conditioner is composed of smooth-edged diamonds. The pad break-in and a dummy wafer run was performed before the CMP tests in order to stabilize the pad surface and material removal rate. The pad surface roughness was measured using a non-contact optical profiler (WYKO NT1100; Veeco Instruments).

Table 1. Experimental conditions.

	AMAT-LK	GNP Poli-762
Head/Platen RPM Ratio	0.96	0.96
Head Down Pressure	2.7 psi	2.4 psi
Slurry Flow Rate	200 mL/min	200 mL/min

Table 2. Slurry information used in the experiments.

	Slurry A	Slurry B
Synthesis	Calcination (Top-Down)	Colloidal (Bottom-Up)
Mean Secondary Particle Size	110 nm	20 nm
Abrasive Content	<1wt. %	<0.1 wt. %

3. RESULTS AND DISCUSSION

The shape and size of the ceria abrasive were characterized by transmission electron microscopy and energy dispersive spectroscopy (EDS). High-angle annular dark field (HAADF) TEM images of the calcined and ultrafine colloidal ceria abrasives are shown in Fig. 1(a) and (b) respectively. The EDS spectra shown in each image confirms the ceria components clearly. In both EDS spectra, O and Ce are detected as major components. As expected, calcined ceria is irregular with sharp-edged particles. In contrast, UFC is spherical and also shows a narrower size distribution than calcined ceria abrasive. The scratch level was compared after stop-on-polysilicon STI CMP with each type of ceria abrasive. Normalized scratch counts for each slurry are shown in Fig. 2. The scratch level from UFC polishing was 80% less than that from calcined ceria, as shown in Fig. 2. Figure 2 also contains representative scratch images: The scratches induced by the calcined ceria-based slurry are longer and wider than those from UFC, which is because the sharp edges and larger size of the ceria abrasive resulted in a higher contact pressure. However, for CMP applications, UFC must have at least an equivalent CMP performance as calcined ceria slurry. Firstly and most importantly, UFC must have a sufficient material removal rate. Using a GNP Poli-762 R&D polisher, the material removal rate was examined. The 2-dimensional contour map of the material removal rate using UFC is shown in Fig. 3(a); this data was obtained using the polishing conditions described in Table 1. Using the same polishing conditions, the same map of removal rate using the calcined ceria slurry was obtained (Fig. 3(b)). The two material removal rate contour maps are similar; therefore, the material removal abilities of UFC are acceptable at this condition. And with this contour map, the non-uniformity of removal rate at each case can be calculated as standard deviation divided by average value. For UFC case, the non-uniformity of removal rate is 4.7% and 12.4% is calculated for calcined ceria case. Based on this result, UFC gives better uniformity in within wafer level. The most important parameter for determining the material removal rate is the pad surface roughness, which changes during the lifespan of the pad. Therefore, it is essential to examine the effect of the pad surface roughness on the material removal rate. For a ceria slurry, the material removal rate decreases as the pad surface roughness increases. Figure 4

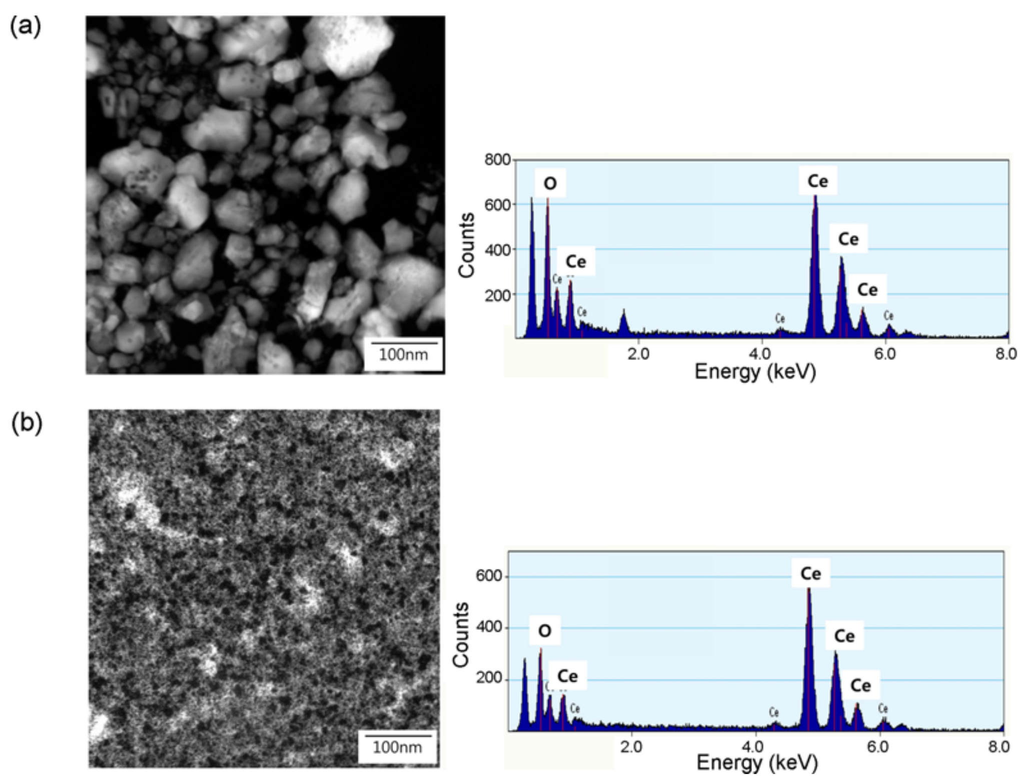

Fig. 1. TEM micrographs and corresoponding EDS spectra of (a) calcined ceria and (b) ultrafine ceria abrasives.

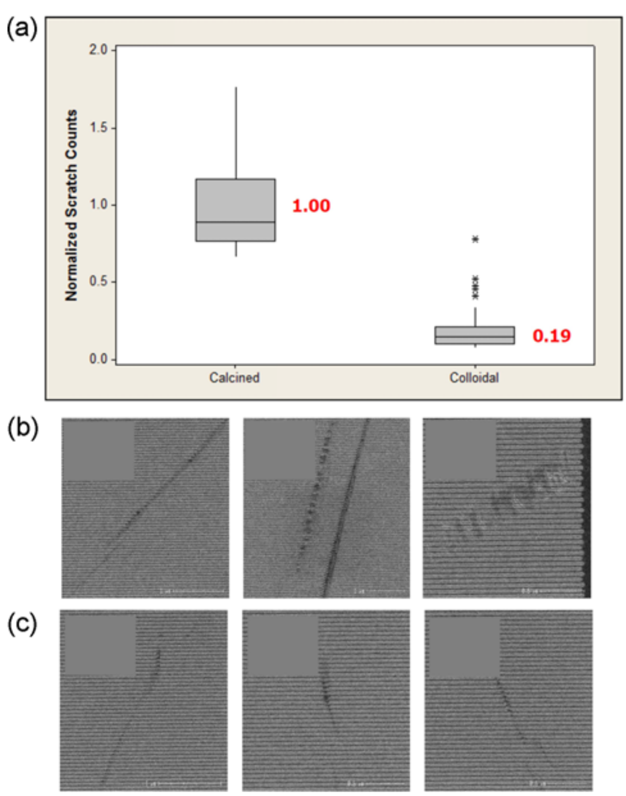

Fig. 2. (a) Comparison of scratch levels from calcined and ultrafine ceria slurries, (b) images of scratches from calcined ceria slurry, and (c) images of scratches from ultrafine ceria slurry.

shows pad surface roughness as a function of the diamond grade of the conditioner. 3-Dimensional optical profiler images of the pad surface are also included. The results indicate the use of conditioners containing smooth-edged diamonds results in a smooth pad surface and a high material removal rate. The effect of the pad surface roughness on the material removal rate is summarized in Table 3. Based on the mechanism of ceria-based CMP, a high contact ratio, i.e., a smooth surface between the polishing pad and wafer surface, plays an important role in determining the oxide material removal rate: A higher contact ratio (i.e. smoother surface) results in a higher removal rate, while a rough surface results in a reduced material removal rate. And the decreasing behavior in the material removal rate with increased surface roughness is not much significant. However, when a UFC slurry was used for CMP, the change in the material removal rate is more dramatically influenced by the pad surface roughness. Experimental results showed that the material removal rate drops from over 2000 Å/min to less than 200 Å/min as the pad surface roughness increases. In particular, a sudden drop in the material removal rate occurs near the surface roughness value of 7 μm. To remove the material, the ceria abrasive must transfer pressure to the wafer surface. However, as the abrasive size decreases, the contact probability is much lower. Therefore, the change in the removal rate using UFC is more dramatic than that of the calcined abrasive. But the exact mechanism needs to be fur-

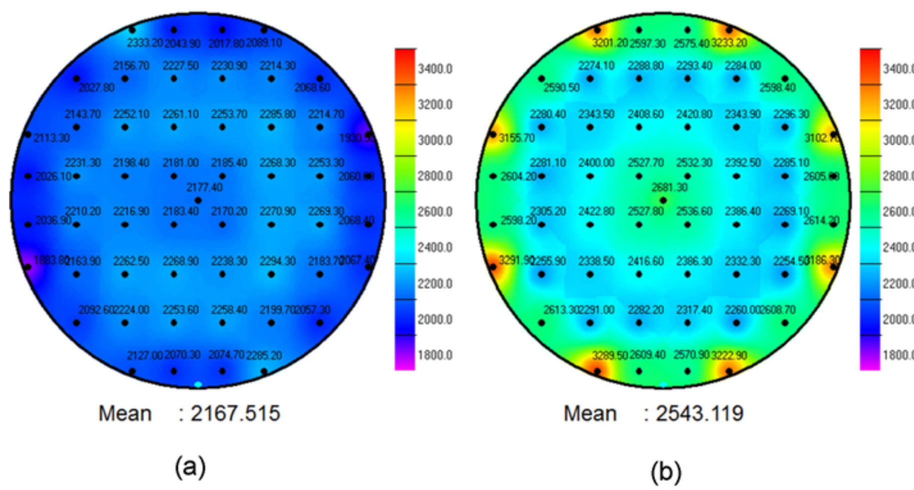

Fig. 3. 2-Dimensional contour map of the removal rate of (a) ultrafine ceria and (b) calcined ceria slurries.

Table 3. Pad surface roughness and corresponding removal rate.

Roughness (μm)	6.65	7.01	7.23	7.96	8.53	8.87	9.55	9.96
Removal Rate (Å/min)		2000 ± 500				< 200		

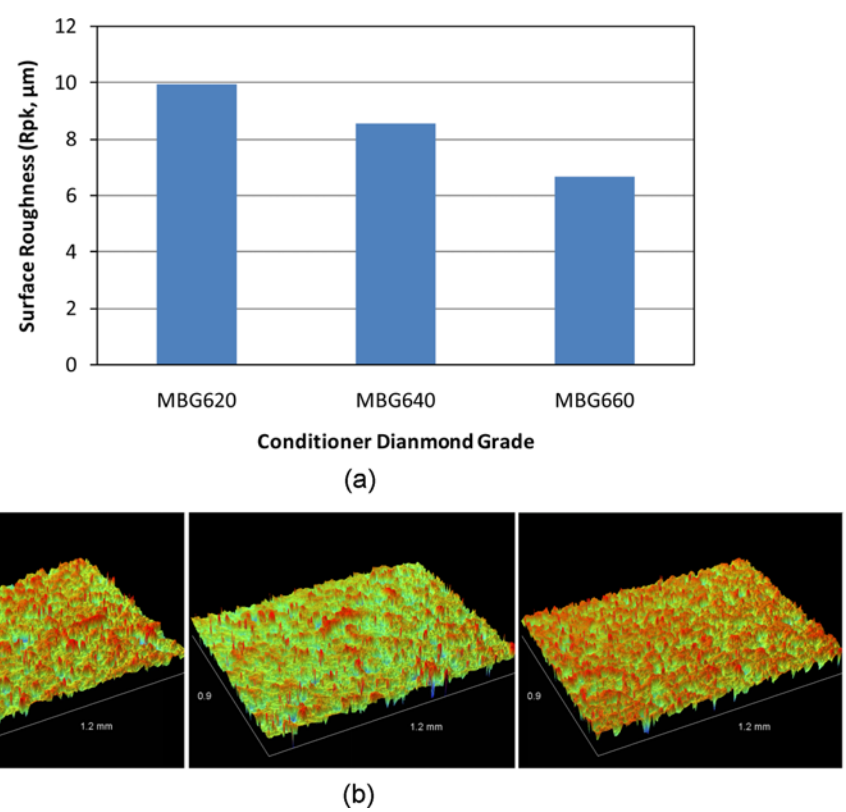

Fig. 4. (a) Surface roughness as a function of conditioner diamond grade, and (b) 3D surface image of each conditioner shown in (a) (MBG620, MBG640, MBG660 from the left image).

ther clarified. The sudden drop and very low material removal rate is not observed using calcined ceria. In order to achieve the advantages of the low level of scratch of UFC with an acceptable material removal rate, the polishing pad surface roughness must be maintained below 7 μm throughout the lifespan of the pad. Therefore, in particular for UFC, conditioning process or selection of conditioner is very important. This paper provided proper conditions for conditioning for UFC. The use of ceria abrasive for CMP is increasing and the size of the ceria abrasive can be controlled. To use ceria abrasives, the structure of pad surface should be optimized in order to obtain a sufficient material removal rate.

4. CONCLUSIONS

In this study, the removal rate of oxide materials using ultrafine colloidal ceria abrasives was explored with respect to the pad surface roughness. The results demonstrated a significant scratch defect reduction when UFC was used as a polishing slurry; however, the rate of oxide removal is sensitive to the surface roughness and ranges from less than 200 Å/min to over 2000 Å/min, but the removal rate variation is not continuous. Although the removal rate with a calcined ceria slurry is dependent on the pad surface roughness, the variation in the removal rate is not as dramatic. When UFC is used for CMP, a minimum surface roughness must be maintained to avoid a significant drop in the material removal rate through the pad lifespan: The polishing pad surface roughness must be maintained below 7 μm to maintain about 2000 Å/min removal rate. Although the material removal rate when using UFC may also be dependent on the polisher, wafer size, polishing material, or polishing conditions, the results of this study suggest the benefits of UFC and provides guidelines for CMP application.

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